



OPTIMIZATION OF THE CONTRAST TISSUE RATIO IN ULTRASOUND CONTRAST IMAGING BY AN ADAPTIVE TRANSMIT FREQUENCY

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Abstract

Conventionnal ultrasound contrast imaging systems use a fixed transmit frequency. However it is known that the insonified medium (microbubbles) is time-varying and therefore an adapted time-varying excitation is expected. We suggest an adaptive imaging technique which selects the optimal transmit frequency that maximizes the contrast tissue ratio (CTR). The method is proposed with the contrast imaging and the harmonic contrast imaging.

Simulations were carried out for encapsulated microbubbles of 2 μ m-radius by considering the modified Rayleigh-Plesset equation for various pressure levels (80 kPa up to 420kPa).

In vitro experiments have been carried out using using a 2.25 MHz transmitter transducer and using a programmable waveform.

We show, through experiments, that our adaptive imaging technique increases the CTR of 2 dB compared to the standard method looking at the central frequency.

By proposing a close loop system whose frequency adapts itself with the perfused media, throughout the examination, the optimization system adapt itself to the bubble population to seek the best trade-off between the bubble response and the transducer bandwidth.

1. Introduction

Ultrasound (US) contrast imaging is being investigated for tissue function and for targeted therapeutic applications with microbubble ultrasound contrast agents (UCA). Currently technical challenge consists in seeking which US excitations should make possible the optimization of the contrast tissue ratio (CTR) :

$$CTR = \frac{E_{bubbles}}{E_{BMF}} . \quad (1)$$

with $E_{bubbles}$ the microbubbles backscattered power and E_{BMF} the tissue backscattered power.

This ratio (eqn. 1) can be maximized if the microbubbles backscattered power is maximized :

$$\max(CTR) \Rightarrow \max(E_{bubbles}) . \quad (2)$$

The transmit signal is a factor of the microbubbles backscattered power.

We tackled the problem in a simple way by proposing an adaptive imaging technique which seeks the transmit frequency that maximizes the backscattered power. The use of an adaptive technique is justified by the fact that:

1. during the clinical examination, the insonified medium perfused by the microbubbles is a non-stationary medium (the concentration and the size of bubbles change...) ;
2. the pressure level is unknown because of the diffraction and attenuation effects which vary from one patient to another ;
3. the size and the distribution of the UCA are not precisely known and can differ from one sample to another.

To overcome these problems, that is to disregard these unknown factors, it seemed more judicious to propose an US excitation whose frequency is selected in an adaptive way.

2. Methods and Materials

2.1 Methods

The optimization aims to maximize the power of the backscattered signal by an iterative method. This optimization was applied in two imaging methods : standard imaging and pulse inversion (PI) imaging [1].

In the case of standard imaging, the principle consists in first measuring the backscattered power for the echo from a sinus wave excitation first and secondly in seeking for the optimal transmit frequency by maximizing this power.

In the case of the pulse inversion imaging, the principle consists in measuring the sum of the both response from 2 inverted pulse first and in seeking for the optimal transmit frequency by maximizing this power of the sum.

The sinus pulse has been modulated with a Gaussian window(fig. 1) [2] to delete the high frequency components responsible of the microbubble destruction. The number of cycles has been fixed to 4, whereas the amplitude has been corrected so that the power level was the same for every frequency.

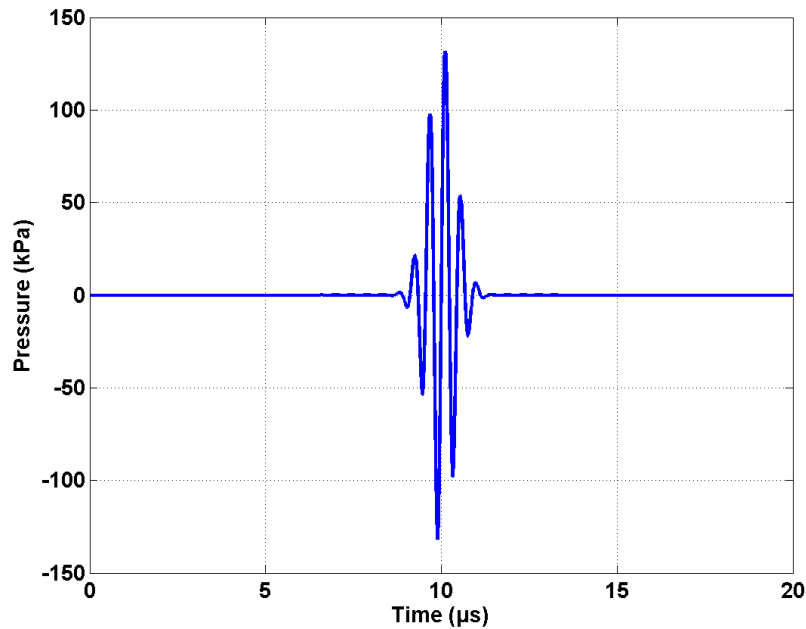


Figure 1. Emission signal with 4 cycles.

The gradient algorithm based on the gradient descent [3] has been chosen to find the frequency of the transmit signal which maximizes the backscattered power. This choice was obvious because the analytic expression of power according to frequency is unknown.

The principle is to maximize the power with a recurrence relation.

$$f_{k+1} = f_k + \alpha_k \cdot \nabla E(f_k) \quad (3)$$

The gradient is estimated with the discrete gradient. This ratio is nearly null for small power in comparison with the frequency and thus the parameters were normalized.

$$E(f_k) = \frac{E_k - E_{k-1}}{f_k - f_{k-1}} \quad (4)$$

For every sign change of two successive gradients, α_k is divided by two.

2.2 Materials

2.2.1 Microbubbles

The ultrasound contrast medium was composed of Sonovue™ microbubbles. The mean diameter is 4.5 μm [4] and the shell thickness d_{s_e} is 1 nm [5]. As for the mechanical shell properties, the shear modulus G_s is 46 MPa [6] and the shear viscosity is 1 Pa·s.

2.2.2 Numerical simulations

Numerical simulations for encapsulated contrast bubbles were resolved, using Bubblesim[7], from the modified Rayleigh-Plesset equation. The Sonovue™ properties were used for the microbubbles parameters. The microbubble echo was computed from only one microbubble immersed in blood. The transducers effects have been considered. Each transmit and received signals were filtered by the bandwidth of the transmit and the received transducers respectively.

2.2.3 Acoustical Measurements

Each method was compiled using Matlab® (Mathworks, Natick, MA). The resulting excitation signal was transmitted through a GPIB port (National Instruments, Austin, TX) to an arbitrary function generator (33220A, Agilent, Palo Alto, CA). The signal was then amplified using a power amplifier (Amplifier Research 150A100B, Souderton, PA) and transmitted to a 2.25 MHz PZT single element (Sofranel, Sartrouville, France) focused at 55 mm and with a bandwidth of 74% (fig. 2).

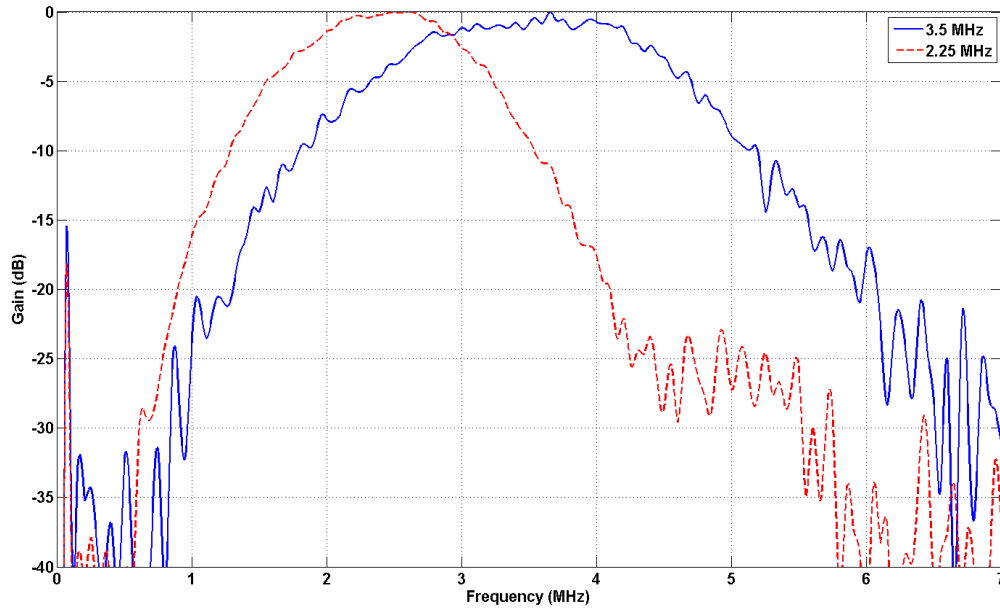


Figure 2. Bandwidth of transducers.

Responses of a 1/2000 diluted solution of Sonovue™ microbubbles (Bracco Research, Geneva, Switzerland) were measured by a 3.5 MHz PZT single element transducer with a bandwidth of 63% (fig. 2) also focused at 55 mm and used in receive mode.

The first transducer was used to transmit the signal, whereas the second which was placed perpendicularly was used to receive the microbubbles echo. This position avoided direct transmission.

Measured echoes were amplified by 30 dB (Panametrics, Sofranel, Sartrouville, France) and then visualized on a digital oscilloscope (Tektronix, Beaverton, OR). Signals were transferred to a personal computer through a GPIB port for further analysis. Finally, each signal was compensated by received transducer bandwidth.

The backscattered power was computed from a linear combination of twenty signals to cancel out the motion of microbubbles. For each iteration, twenty pulses were transmitted and twenty signals were received. With a principal component analysis (PCA), a new received signal which allows to deduce the backscattered power, is computed.

To deduce the contrast tissue ratio (CTR), the microbubbles were injected in a blood mimicking fluid (BMF) "EU-DFS-BMF-ver.1.2" (Dansk Fantom Service, Jyllinge, Denmark). For each frequency, the BMF received power (without microbubbles) was determined.

3. Results

3.1 Simulations

The first simulations allowed us to know the function at maximizing. The next simulation optimized adaptively the backscattered power in standard imaging and in pulse inversion imaging, respectively.

In standard imaging, to know the evolution power according to the frequency, a microbubble has been stimulated with 4 cycles and the backscattered signal has been computed for different pressures.

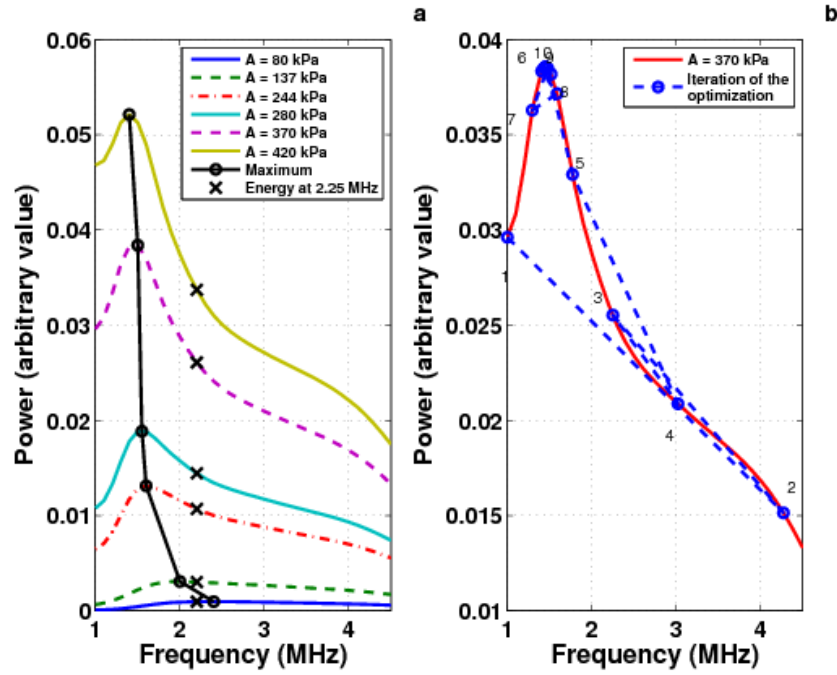


Figure 3. Power according to the frequency for a 2-microns microbubble in standard imaging.

The frequency which allows to obtain a maximum power varies with the pressure: for a high pressure, the frequency is lower (fig. 3). From the appearance of power, the initial frequencies for the algorithms have been chosen to find the global maximum.

The methods was applied with three signals of 244 and 370 kPa maximal pressure.

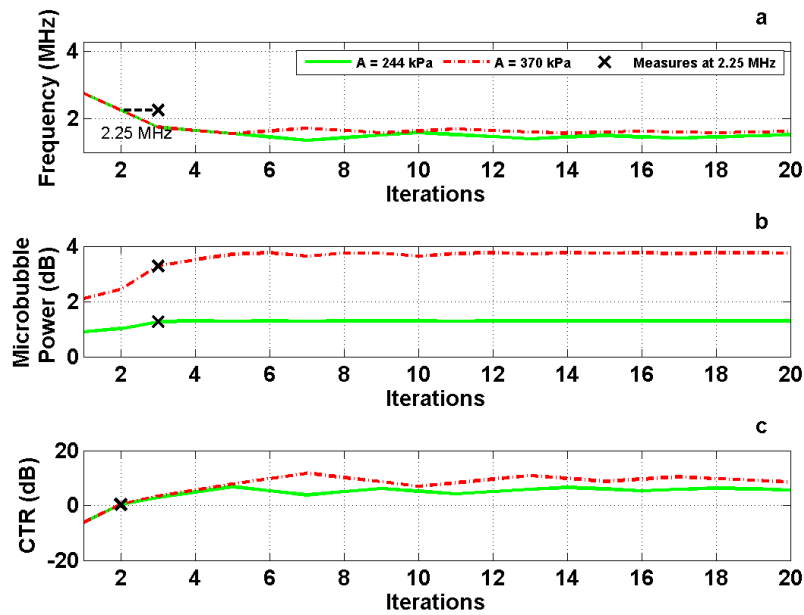


Figure 4. Simulation : Gradient ascent for a 2-microns microbubble in the standard imaging.

The backscattered power was stable and maximize after twenty iterations. For each pressure, the optimal frequency is different (1.6 MHz and 1.39 MHz respectively for 244 and 370 kPa), which was shown by the power according to the frequency.

The simulation has been reproduced by adding the pulse inversion.

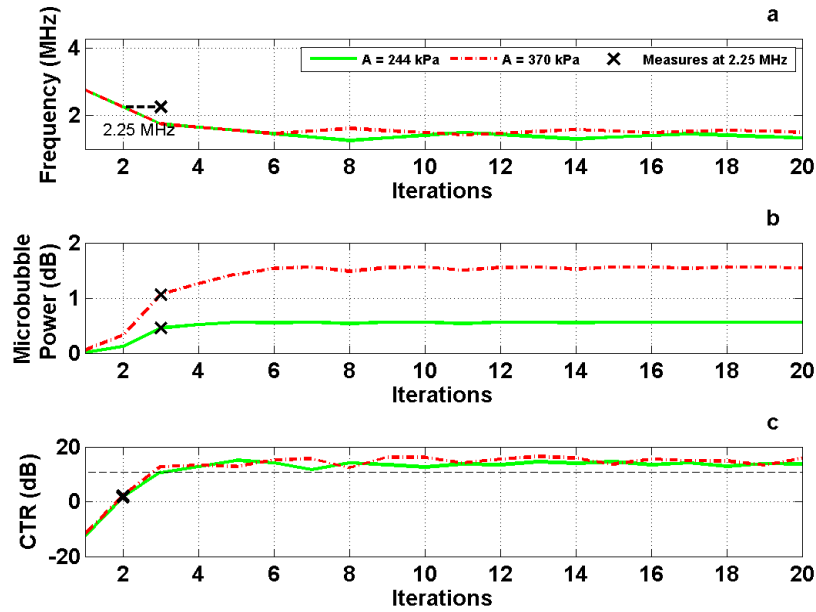


Figure 5. Simulation : Gradient ascent for a 2-microns microbubble in the pulse inversion imaging.

In the case of the PI imaging, the methods can optimize the contrast until 14dB. The optimal frequencies were 1.53 MHz and 1.37 MHz respectively for 244 and 370 kPa .

3.2 Experiments

A cloud of microbubbles immersed in BMF has been stimulated with two different pressures (244 and 370 kPa).

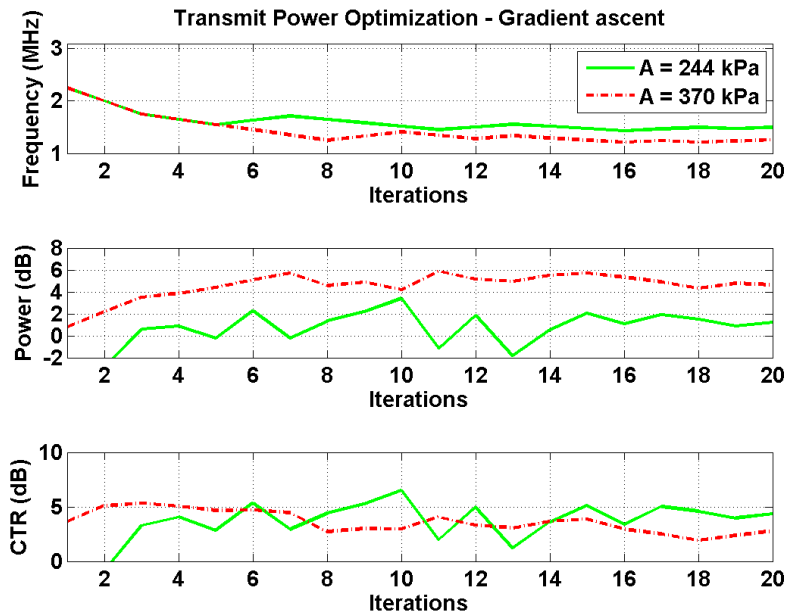


Figure 6. Experiment with gradient ascent in the standard imaging.

The optimal frequency is different according to the pressure (1.4 MHz and 1.2 MHz respectively for 244 and 370 kPa) in standard imaging. The CTR can reach 6 dB.

The same experiments have been reproduced by adding pulse inversion.

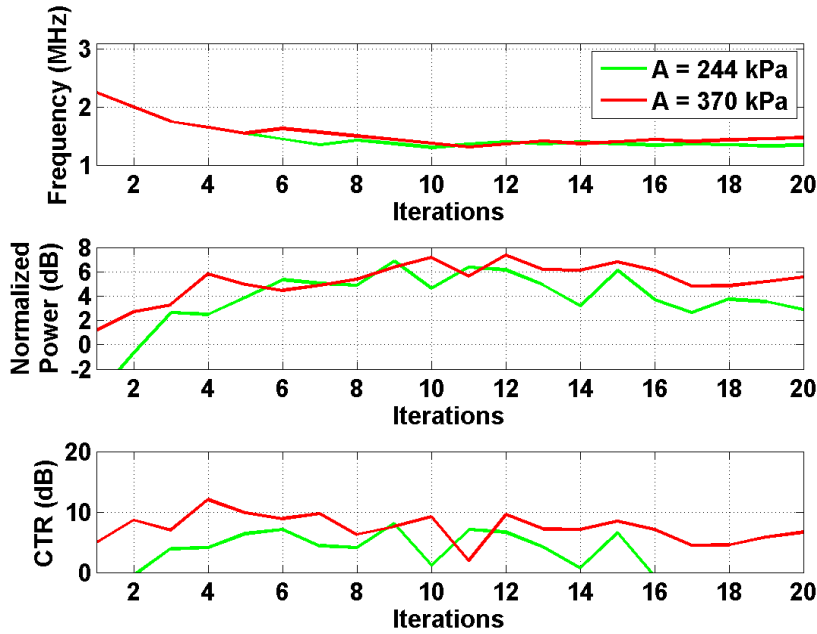


Figure 7. Experiment with gradient ascent in the pulse inversion imaging.

The backscattered power was optimized and stable after around ten iterations. The optimal frequency is different according to the pressure (1.45 MHz and 1.3 MHz respectively for 244 and 370 kPa) in standard imaging. The CTR can reach 11 dB.

4. Discussions

The backscattered power has been optimized in standard imaging and PI imaging. Our method was not dependant on the imaging method. The optimal frequency was different according to the pressure and the imaging method.

The optimal frequencies depend on the transmitted pressure. The backscattered power according to the frequency shows that the maximal power shifts forward the low frequency when the pressure increases. The simulations and the experiments optimal frequencies (for the highest pressure) are lower than these ones for the lowest pressure. The optimal frequencies obtained in simulation are near to these obtained in experiments.

The CTR is optimized with the maximization of backscattered power.

The experimental results are not exactly identical because of the non-stationarity of microbubbles. To cancel their motion, we have repeated the experiment. But a high number of repetition and a high value of iterations number could destroy the microbubbles and thus the power could decrease. A trade-off must be found to avoid the destruction of the microbubbles.

5. Conclusion

The optimization allows to maximize the backscattered power and thus to maximize the CTR. These methods allow to find the optimal frequency adapted to microbubbles in standard imaging and in harmonic imaging. However, these results could be improved if the tissue backscattered power is minimized.

We can carry on adapting our method with a ultrasound scanner.

Acknowledgement

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